MARS ON GLACIAL EPOCHS.

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1. Croll's ingenious theory that eccentricity of orbit combined with axial tilt produced our glacial periods challenges comparison outside the earth. And an example lies ready to its hand, in the planet Mars. For Mars not only presents appearances singularly suggestive of our polar snows, but stands so conditioned in eccentricity and tilt as to promise a criterion of a crucial character.

In consequence such appeal was very soon made and with the result of a seemingly complete denial. Although admirably circumstanced to exemplify the theory Mars did nothing of the sort. No marked preponderance of snow distinguished the hemisphere which glaciation should have covered. The ill-conditioned one showed as conclusive a snow-sheet as its fellow. Eccentricity apparently was powerless to effect vitally deposition about the pole.

This was more than a quarter of a century ago, and the last quarter of a century has revolutionized our ideas of the physical condition of Mars. Especially in the matter of water, we now have knowledge which has particular bearing upon the subject. We no longer believe Mars to be a counterpart of the earth. Among much that is analogous we see much that is the reverse; and with the flight of the similar the cogency of the argument departs. In the light of this change it becomes advisable to reopen the case; and I therefore make bold to introduce it to the notice of the Society.

2. Round about those parts of Mars which the motion of the markings point to as the planet's poles may be seen two roughly circular white patches, sharply contrasted with the other features of the disk. Each is fairly regular in shape, but changes in size according to what more particular inquiry shows to be the changing seasons of the planet's year. When the one patch is large the other is small; and as the one waxes the other wanes, the mass of white shifting from pole to pole with a certain chronometic cadence. Both appearances and behavior commended them to Sir William Herschel for polar snows, and such they have generally been considered since. Indeed the more minute our study of them, the more they seem to justify the imputation.

3. The obvious simplicity of this explanation, however, has tempted some ingenious minds to see in the exhibit not frozen water, but frozen carbonic acid gas. For under great stress of cold, carbonic acid not only takes refuge in the solid form, but does so with all the delicate purity of snow. The transformation demands, indeed, a very low temperature and to this end was the idea invented; inasmuch as the distance of Mars from the sun seems hard to reconcile with a mean temperature comparable to that of our earth. Now as it is of the first importance to the inquiry before us to be as certain as possible whether it be really snow or ice that we gaze upon over there in space, I make no circumstance of confronting at once this hypothesis.

Plausible as the suggestion of carbonic acid sounds, examination of the fitness of the substance for the place discloses one fatal defect. Carbonic acid and water agree well enough in their solid state and are not incompatible in their gaseous one, both being then invisible; but they are not at all at one upon their intermediate condition. As fluids their behavior is quite diverse, and Mars chances to exhibit the very effect which this diversity should cause. It is a peculiarity of carbonic acid that it is not at home as a liquid, passing, except under great pressure, at all temperatures practically instantaneously from the solid into the gaseous state. Under one atmosphere or less the curves representing the melting and the evaporation points of this substance lie almost side by side. And they do this as conclusively at very low temperatures as at relatively high ones. Carbonic acid insists on volatilizing. Thus no place is left in the economy of its behavior for a permanent liquid, whatever the degree of cold.

Now, one of the most striking features of the polar caps is the unmistakable exhibit of such a liquid. Seventy years ago, Beer and Mädler noticed a dark band surrounding the northern cap, but the full significance of the observation seems to have escaped deduction. Since then several observers have noted this band on one or other of the caps; and W. H. Pickering, in 1892, added a most significant detail, a large bay connected with the one about the southern cap. Farther study has brought out still more detail of the sort. Under this scrutiny the character of the phenomenon appears in so clear a light as to preclude mistaking its import.

The state of things seems to be this: So soon as either cap begins to shrink, there proceeds to surround it a blue belt. The belt increases with the increased rate of diminution of the cap and decreases as that diminution falls off; meanwhile, it keeps pace with the cap, shrinking with it so as always to border its outer edge.

It is difficult to conceive how anything could more conclusively proclaim itself the liquid product of the disintegration of the cap. This badge of blue ribbon seems to mark the substance as H_2O.

4. Against this pronounced appearance and decisive conduct on the part of the cap, what difficulties have we to oppose to its acceptance for what it purports to be? Two such present themselves, both on the score of general temperature: first, the less heat received by the planet due to its greater distance from the sun, a heat only the moiety of what falls to our lot; secondly, a thinner air at the surface than that we know, perhaps in amount but a seventh that of our own. Are either of these objections fatal? Upon scrutiny I think we shall see that neither of them necessarily is so, on account of certain counterbalancing facts.

5. In the first place, not all the heat intercepted by the earth reaches its surface which might do so, quite apart from what is necessarily reflected. From the commotional character of our sky, it is safe to say that the earth fails of half the heat it would receive were that sky perfectly clear. What with storms, passing clouds and haze, fully more bar than passage is offered to the rays. Now the Martian sky is clear, perpetually so. All the heat a pure sky permits of passage falls unhindered upon the soil. Its frugal atmosphere wastes nothing. Thus receptivity makes up what distance denies.

6. As regards the second point, it used to be thought that air, pure and simple, furnished the earth with the cloak that kept out the cold of space. But it is no longer considered thus effective. Tyndall made experiments on the subject to the deduction that not air, but water vapor it was that did the business. Since then the enormous preponderance of power ascribed by him to water vapor has been questioned; but experiments to disprove it labor under the disquieting impossibility of excluding the vapor itself from the test. To get perfectly dry air is as difficult as to get a perfect vacuum; and the least trace of water vapor is potent to vitiate the whole transaction.

As figures are here of importance I shall quote him on the subject. In his "Rede" lecture at Cambridge, in 1867, Tyndall says:

"Compared with the great body of the air, the aqueous vapor it contains is of almost infinitesimal amount, 99½ out of every 100 parts of the atmosphere being composed of oxygen and nitrogen. In the absence of experiment, we should never think of ascribing to this scant and varying constituent any important influence on terrestrial radiation; yet its influence is far more potent than that of the great body of the air. To say that on a day of average humidity in England the atmospheric vapor exerts one hundred times the action of the air itself, would certainly be an understatement of the fact; . . . . and I am not prepared to say that the absorption by this substance is not two hundred times that of the air in which it is diffused."

And below he goes on:

"Probably a column of ordinary air ten feet long would intercept from ten to fifteen per cent. of the heat radiated from an obscure source, and I think it certain that the larger of these numbers fails to express the absorption of the terrestrial rays effected within ten feet of the earth's surface."

But England has a very moist climate. If, then, the trace of vapor there be but the $\frac{1}{200}$ part of the whole, much less must it be elsewhere. If we call it one $\frac{1}{500}$ part of the main body of the air, in the drier regions of the earth, and consider the Martian atmosphere at the surface of the planet to be one-seventh of our own at sea level, the vapor tension might be as great as ours and yet the total amount of vapor present but $\frac{1}{70}$ of the whole atmosphere. In which case it would render that air as effective a covering as our own. I am far from saying that this is the case; the more so that, as we shall presently see, there are local conditions which, in the event of its being as copious as, would render it much more effective than, our own. But it is worth noting how little we need go out of our way in possibilities to furnish Mars with sufficient covering.

7. While we are on the subject of carbonic acid, we may note that that gas shows, unlike water vapor, remarkable exclusiveness in the absorption of heat. Ångstrom finds its absorption belt in the spectrum very circumscribed, and in the lecture quoted above Tyndall tells us that practically it absorbs no heat but what radiates from carbonic acid itself. Such domesticity limits its absorptive efficiency in the world at large. The result of which is that there would be a tendency to equalize its deposit over the whole planet; for the surface covered by carbonic acid snow would

be kept warmer and the surface bare of it colder than each otherwise would be until carbonic acid was deposited over the whole.

8. From the foregoing it is clear that the amount of moisture consonant with temperate conditions upon the planet does not require to be great. We need, therefore, feel no surprise that spectroscopy should as yet give us uncertain answer on the subject. Huggins found marks of the presence of water vapor in the planet's spectrum; Campbell could find none. And the latter thought he should have done so had the amount been so much as one-fourth of our own.

But there is another drawback to this deduction. It is possible to point out a fallacy in the assumption of the data upon which the detection depends. We are told that the light examined has passed twice through the Martian atmosphere. But this is not the fact. A part of it has done so indeed, but only a part. A considerable portion has never traversed that atmosphere at all. We should know *à priori* that this could not but be the case. But we are not left to *à priori* reasoning in the matter. We have direct evidence of the fact. One of the peculiar details of the disk the planet shows us is the presence over a part of it of a veil which is not only unmistakable but pronounced. This veil is known as the limb-light. Extending in from the limb along its whole length is a brilliance strong enough to swamp all but the heaviest markings for a distance in of thirty degrees. Circumstances of position show that this can only be the effect of an atmosphere (*Annals Lowell Observatory*, Vol. I). It must extend over the whole disk, but becomes conspicuous only as we approach the limb, owing to the greater depth of it passed through as we increase the inclination. It should vary roughly, though not exactly, as the cosecant of the angle in from the limb. The effect might be due to anything suspended in the air—dust or water vapor. It does not seem possible as yet to evaluate it satisfactorily, but from its action it would appear to bear no inconsiderable ratio to the rest of the illumination. Suppose this ratio to be one of equality—and the amount of obscuration it effects show this to be no unseemly supposition—then its presence would halve the precision, and instead of being able to detect a quantity one-fourth of our own, we should only be able to perceive the double of that.

9. Now, whatever moisture there be on Mars—and water there must be to some extent, since otherwise no seasonal change could

occur, and that such change does take place is an indisputable fact of observation—such moisture would be rendered more potent there than it is on the earth by two Martian specialties in the matter of climate: first, the condition of the sky by day and, second, the state of the sky by night.

The day-sky on Mars is distinguished by being almost perpetually clear. From dawn to dusk daily and from the year's beginning to its close, the sun shines down upon the planet's surface out of a heaven unflecked by cloud. I have mentioned this above, but one deduction from it I want to bring forward more prominently. Not only does a clear sky give ingress to warmth by the absence of cloud, but if it contain water vapor it plays in addition the part of cloud itself. It exerts the efficiency of cloud and the efficiency of sunshine combined. For it lets in the warmth and then will not let it out again. In short, this transparent moisture suspended in mid-air is as a glass to make of the planet a conservatory. And when we reflect that this is true all over the planet at all times, we see that even the chief disturber of such a state of heat accumulation, the influx of cold winds from elsewhere, is as much as possible stopped.

The importance of this solidarity in fair weather climate can hardly be overestimated. It is the indraught of colder winds that thwarts that hothouse heightening of the temperature which we experience in the days called weather-breeders. It is true that the coldness of the incoming winds is consequent on many causes, and universal sunshine would not avail to prevent a fall of temperature due to such circulation; but a general heating of the ground, especially to the northward, would certainly temper its effects, not so much by equalizing the extremes, if indeed it would do this at all, as by raising the means.

10. The night-sky on the planet abets the action of the day one. Just as the day sky is cloudless so the night-sky apparently is cloudy. This is the outcome of Mr. Douglass' study of projections upon the terminator. By first observing and then classifying over four hundred of such projections, he came to the conclusion that the appearances could not be produced by bodies contiguous with the planet's surface. In other words, the optical effects were not such as could be caused by mountains, but were such as could be caused by cloud. Thus interpreted he finds that, though the sky is fleckless all day, at sunset clouds begin to form, showing their presence by

the way in which they are lit up into the night after the sun has set to the ground below. In like semblance of beacons he finds them out beyond the sunrise terminator, heralds of the dawn.

Whether the cloud canopy has been continuous the night long we cannot of course positively affirm. That it has been so seems probable, inasmuch as the conditions which caused it to form would continue to some extent on through the night. The surface would grow colder and colder, thus keeping up the condensation into cloud above it. And this state of things would last till sunrise, as the coldest moment, so far as the heat received from the sun goes, is the moment before the dawn. That at that time we find the clouds still there is strong presumption that they have not left their posts during the night. The effect of such a cloud canopy to the planet during the night hours is as important as the lack of it was important by day. It effectually shields the surface from depleting radiation. It thus helps husband what the day garnered of heat. It acts again the part of the glass in a greenhouse.

11. So much on the score of authenticity of appearance presented by the Martian polar caps—so much, that is, toward the establishing that they are what they purport to be.

From the constitution of the caps we pass now to the second point in which the planet recalls our own for purposes of glaciation, to wit: in the character of its orbit. The caps show us apparently that the necessary material is present; the orbit assures us that the necessary cosmic conditions are fulfilled.

At the present time the orbit of Mars is possessed of an eccentricity about five and a half times our own. Our earth's is .0168; that of Mars .0933. The planet's axial tilt, too, is consonant with the conditions of a criterion; for it is closely accordant with the earth's. According to Schiaparelli, who has made the last and undoubtedly the best determination of this tilt, the planet's equator is inclined to its ecliptic 24° 52′. That is 25°—for the quantity cannot be found to within the nicety of a few minutes—represents on Mars what $23\frac{1}{2}°$ does on the earth, the tilt of the planet's poles and the consequent breadth of its arctic regions. The slight difference between the two values would simply increase by so much the theoretical effect of the eccentricity.

We have then in the case of Mars at the present moment both eccentricity and tilt, such as to enhance whatever effect might be expected. For by an odd coincidence it so chances that these essentials are circumstanced nearly the same. In both planets the solstices fall not far from the line of apsides. What is more, it is the same solstice that occurs near perihelion in each case. Mars comes to perihelion in longitude 153° 4)′ and to the summer solstice of his northern hemisphere in longitude 176° 48′; our earth reaches the like points in her orbit, the perihelion in longitude 281° 21′, the summer solstice of her northern hemisphere in longitude 270° 14′ respectively. Thus both planets pass those points, whose near coincidence is vital to the effective working of the eccentricity, in close succession. With Mars the summer solstice follows perihelion; with the earth it precedes it. This has the effect in the northern hemisphere of clipping the Martian beginning of summer as compared with its end, and of curtailing the mundane end of it as compared with its beginning; similarly in the southern hemisphere of both with regard to winter.

Curious it is that both planets should turn to the sun their corresponding hemispheres correspondingly—an agreement in inclination which permits of paralleling, by what may at the moment be discerned on Mars, what would happen on the earth during an accentuation of eccentricity such as is invoked to account for a glacial period. It would show itself, too, under magnification. For the greatest maximum possible to the earth's eccentricity is, according to Leverrier, .0747, or a fifth part less than that of Mars now.

21. Having surveyed the situation, material and mechanical, we may now turn to the phenomena. When we do so we are confronted at once upon the planet by what appear to be unmistakable polar caps, fairly comparable with our own in size and behavior, but with a difference. Ours are first distinguished by their greater extension. In our northern hemisphere the ground in winter is covered by a permanent mantle of snow down to about latitude 45°. This represents our snow-cap at that season, as it would appear to an outsider. In this we live and move and have our being for some four months, and it is at least a pregnant thought that to such an outsider the highest development of life upon our planet should seem thus for nearly half the year to have its existence within the polar cap. It opens our eyes, abstractly as well as personally, thus for a moment to see ourselves as others see us. Our northern polar snow-cap, then, covers on the average round the globe 90° or more at its most. If we take occasional snowfalls into account the maximum might be considerably stretched; for snow sometimes not only

falls but lies below latitude 35° both in America and Asia, and if our sky were clear, as that of Mars is, would be distinctly perceived by an onlooker as part, even if a detached part, of the polar cap. From its maximum the cap then dwindles till at its least, about two months after the summer solstice, it has so shrunk as to measure only about 40° across.

With regard to our southern cap, it is not possible to affirm so positively either the maximum or the minimum because of the presence there of surrounding oceans. Nevertheless it is apparent, from the greater cold of corresponding southern latitudes, that at its greatest the cap would exceed its northern fellow if duly given ground; while the summer glaciers of Terra del Fuego show that it would probably be the greater of the two at its minimum as well.

Now on Mars the northern cap attains at its height a width of 70°, which event occurs about one hundred of our days, or fifty-three of its own, after its winter solstice. About the middle of February this date corresponds to on earth. It then decreases regularly to its minimum, which takes place about the same time after its summer solstice. Near the minimum it remains some time. At this, its smallest compass, it measures only some 3° across.

Confining ourselves now for the moment to what we can directly compare, the northern caps of the two planets, we find a difference in relative size between them at both their extremes in the same direction. That of the earth is bigger than that of Mars, both at maximum and at minimum. As to the maximum, this happens in spite of the fact that the Martian year, and therefore the Martian winter, is nearly twice as long as our own, so that for nearly double the time any given northern latitude there is tilted away from the sun.

This is not all. If we express analytically the area of a zone embracing the pole of given breadth in degrees θ, we find for its value

$$\int_{\theta=0}^{\theta=\theta}\int_{\phi=0}^{\phi=2\pi} r^2 \sin\theta \, d\theta . \, \delta\phi$$

Where r is the radius of the sphere, φ the azimuth and θ the polar distance,

$$= -2\pi r^2 \cos\theta \Big|_{\theta=0}^{\theta=\theta} = 2\pi r^2 (1-\cos\theta)$$

From this we see that the maxima and minima on the earth are as five to one; while on Mars they are as 130 to one. The ratio of decrease due to summer melting is then twenty-six times as great in the latter case as in the former.

To the belief that Mars lacks warmth this comparison is calculated to give a shock of surprise. But however that be, we come next to an even more unexpected result.

13. This next feature is the difference in behavior of the two caps. At its greatest the southern cap surpasses the northern one; at its least it falls below it, passing it the other way.

It is both bigger in winter and smaller in summer than its northern counterpart. It thus outdoes its fellow in action generally—in accumulation first, in dissipation afterward. Beer and Mädler stated this long ago, though curiously enough upon quite erroneous data. Surprising as the circumstance is—for it becomes more surprising on consideration—I think it can be shown to be the fact.

In the case of the maxima direct data on the point are lacking. The maxima are not easy to determine, owing to the tilt of the axis and the fact that the solstices occur nearly at the apsides, and they never have been determined. We have, with two exceptions, only determinations made a long way one side or the other of the date of the maximum. One of these exceptions was that of Sir William Herschel, made six months before its summer solstice, and therefore about 145 days after its winter one. In 1781 he estimated the diameter of the southern cap at 60°.

In 1798 Schroeter made it 50° four months before the summer solstice. While Mädler in 1837, at the time of the winter solstice, estimated it at 70°. It is quite possible that he mistook some of the southern islands for the cap, a mistake made by more than one observer. No further approach to a maximum is recorded till Schiaparelli observed that of 1882, 150 days before the summer solstice, at 45°. All of these were too far away from the true time of the maximum to give even approximations of it.

The second exception was the determination made at Flagstaff in 1896–97 on the north pole, of which a transcript follows. The extent of the cap has been got by taking its width from the figure (*Annals Lowell Observatory*, Vol. ii, page 232) between two given dates; and the number of days before the solstice has been put as the mean of these two dates.

Width of Cap.					Days after winter solstice.	Days before summer solstice.
Jan.	11–Jan.	25	50°	Jan.	48	
	17– "	28	47		55	
	31–Feb.	10	60	Feb.	78	
Feb.	6– "	17	72	"	90	
	13– "	21	71	"	100	260
(Mar.	22–Mar.	30	77	Mar.	174)	
	23– "	31	73		177	183
	26–Apr.	4	72	"	182	178
	29– "	7	63	Apr.	188	172
Apr.	1– "	11	63	"	197	163
	13– "	20	58	"	218	142
	16– "	26	49	"	230	130
	24–May	2	51	"	245	114
May	26–June	4	22			43
	28– "	6	18			39

It will be seen from this that we have but two determinations at all to the point—those of 1781 and 1897—and neither of these as definite as is desirable.

That the maxima apparently occur about one hundred days after the winter solstices of their respective hemispheres we can gather from the observed times of the minima, of which we know very much more. But we can only surmise this, subject to future correction.

Although the direct data are thus inconclusive on the subject of relative size, there are, however, what we may call indirect data in the case. If we compare the two caps at corresponding periods before the time of solstice we shall get a fair idea of their state midway in their career. And for this comparison we do possess very respectable data, since at this stage both caps have been fairly often and fairly well observed. Tabulating all the records from ninety-two days before to thirty days before their respective summer solstices for the two caps, we have the following list:

South Cap.				North Cap.			
Days before summer solstice.		*Size.*		*Days before summer solstice.*		*Size.*	
1862	48	36°	Lord Rosse	1882	82	20°	Schiaparelli
1877	34	29°	Schiaparelli		77	27°	
1890	63	30°	"	1884	84	30°	
	55	25°			76	28°	
	48	25°			65	25°	"
	35	20°	"		55	25°	
1894	89	50°	Lowell Obsy.		46	22°	
	76	39°			35	25°	
	69	37°		1886	85	30°	
	52	31°			55	21°	"
	44	25°			32	12°	(mean)
	42	13°					
	33	27°		1897	43	22°	Lowell Obsy.
					39	18°	
				1899	92	40°	Flammarion & Antoniadi
					77	35°	
					75	36°	
					58	33°	
					41	30°	

	South Cap.	North Cap.
Days before summer solstice.	*Mean.*	*Mean.*
92–80	50°	30°
80–70	39	32
70–60	34	25
60–50	28	26
50–40	25	25
40–30	27	18

From this it appears that from ninety-two days to thirty days before their respective summer solstices the southern cap is continuously larger than the northern one. Furthermore, that it exceeds the latter most the farther away it is from the solstice. From which we may conclude that at its maximum it also surpassed the latter.

Any correction for irradiation would but increase the contrast, since the north polar cap is necessarily observed from a much greater distance than the southern one when seen thus near its summer solstice; and the irradiation being the same for both in seconds of arc becomes, with decreased size of disk, greater as measured in Martian degrees.

14. As a preliminary to an explanation of this phenomenon, it is necessary to consider the general laws of planetary insolation, or, in other words, the amount of heat received from the sun by different parts of the planet at different times.

The total quantity of heat intercepted by the planet as a whole in passing from any point of its orbit round to the same point again is a function of the eccentricity of the orbit. For heat or light, like gravity, diminishes inversely as the square of the distance. But the quantity of gravity received, if we may so express ourselves, is measured as follows:

Since equal areas are swept out by the radius vector in equal times, or $r^2\, d\theta = h dt$; and since $c g_1 = \frac{1}{r^2}$

$$c.\, h.\, dt.\, g_1 = d\theta$$

or

$$h\, C.\, G. = 2\pi$$

where $G =$ total gravity received during a revolution. Now if the major axis of two orbits be the same, the period is the same. Consequently in this case G varies inversely with h. But

$$h = \sqrt{\mu a (1 - e)^2}$$

whence

$$a h^2 = \mu b^2$$

$$h = \frac{b \sqrt{\mu}}{\sqrt{a}}$$

Whence the total gravity and consequently the total heat received varies inversely as the minor axis of the orbit, and is therefore a function of the eccentricity.

15. But the relative amount received in passing from one equinox to the other does not vary but is the same, as D'Alembert showed, from whichever equinox we set out. That is, the planet has as many units of caloric fall upon it in traveling from the vernal to the autumnal equinox as from the autumnal to the vernal one. Indeed, whatever point we are pleased to take for starting point,

180° journey out will see as many calories reach it as the subsequent journey of 180° in. For

$$r^2\, d\theta = hdt.$$

whence

$$d\theta = \frac{h\, dt}{r^2}$$

That is the angle swept over is at all points proportional to the amount of heat received, since this amount is always inversely as the square of the radius vector.

16. Thus the heat received through any angle is independent of the eccentricity. But it is not independent of the axial tilt. The amount of heat received at any point, in consequence of the tilt, depends upon the position of the point. At the pole it varies from nothing for the six months about the winter solstice to

$$\int \frac{1}{r^2} \sin \delta .\, dt = \int \frac{\sin \theta \sin \varepsilon .\, d\theta}{h}$$

for the other six about the summer one.

For a hemisphere, taken as a whole, the total summer insolation much exceeds the winter one (Weiner, Ueber die Stärke der Bestrahlung, *Zeitschrift der Oesterreichischein Gesellschaft für Meteorologie*, 1879; also Sir Robert Ball, *The Cause of an Ice Age*, 1892).

Let $2H$ be the amount of heat falling on a section equal to the earth at unit distance in unit time, and let δ be the declination of the sun.

Then the amount received by one hemisphere at distance r in the time dt will be

$$\frac{H}{r^2}(1 + \sin \delta)\, dt$$

and by the other

$$\frac{H}{r^2}(1 - \sin \delta)\, dt$$

but

$$r^2\, d\theta = hdt$$

whence the above

$$\frac{H}{r^2}(1 + \sin \delta)\, dt$$

$$= \frac{H}{h}(1 + \sin \delta)\, d\theta$$

again, since $\sin\delta = \sin\theta \sin\epsilon$, where $\epsilon =$ obliquity of the ecliptic the above becomes from equinox to equinox

$$\int_0^{\pi} \frac{H}{h}(1 + \sin\epsilon \sin\theta)\, d\theta = \frac{H}{h}(\pi + 2 \sin\epsilon)$$

and for the other hemisphere

$$\frac{H}{h}(\pi - 2 \sin\epsilon)$$

With $\epsilon = 24° 52'$, the present received value on Mars, we have the two in the proportion of 63 to 37.

But though the summer and winter insolation thus differ, they are the same for each hemisphere in turn. Consequently the above cannot be the cause of the differences in question between the respective maxima and minima of the polar caps.

17. Not the amount of heat but the manner of its reception, then, is responsible for the difference we observe. Looking at it in this light we shall detect certain diversities of position competent possibly to the result.

Of the opposite variations presented to us by the two caps, the one most difficult to detect is the easiest to explain. The difference in the maxima seems to be due to the surpassing length of the antartic night.

Owing to the eccentricity of the orbital ellipse and the position of the solstices, the southern hemisphere is both farther away from the sun during its winter and is so for a longer time. The arctic polar night is 306 of our days long; the antarctic 381. Thus for seventy-five more days than happens to its fellow, the southern pole never sees the sun. Now since the total sunlight from equinox to equinox is the same in both hemispheres, its distribution by days is different. In the northern hemisphere the same amount is crowded into a smaller compass in the proportion of 381 to 306; that being that hemisphere's relative ratio of days. But since, during the winter, there is a balance of accumulation over dissipation of snow, each twenty-four hours must on the average add its tithe to the sum total. The northern days, being the warmer, each add less than the southern ones; and furthermore there are fewer of them. On both these scores the integral of the additions about the northern pole is less than about the southern one. Consequently the snow sheet is there the less developed.

18. With the minima the action is otherwise. Inasmuch as the greater heat received during the daylight hours by the southern hemisphere is exactly offset by the shortness of its season, it would seem at first as if there could be no difference in the total effect upon the two ice-caps.

But further consideration shows a couple of factors which might, and possibly do, come in to qualify the effect. One is that the diurnal heat, being more intense though not so long continued, might work to more advantage. For the water would be the more likely to flow away the greater was the quantity of it manufactured ; or if it were caught up into the air more of it would be wafted away beyond reach of refreezing. It is the freshly acquired mobility that does the business. As ice the substance is chained to the spot ; as water or vapor it is free to roam ; and natural conditions at once transport it out of the region and so out of the problem.

The second factor is due to the action of the intervening nights. The vapor set free during the hours of sunshine is not all deposited during the night, as is witnessed by the presence of sunrise clouds. Such part as is not precipitated forms a blanket for the ground, preventing the heat of the surface from being radiated off into space. The greater the evaporation during the day the denser, other things equal, would be the cover-lid at night and thus the less heat be permitted to escape. This saving of heat is just so much to the good in the struggle of relative dissipation on the side of the southern hemisphere. The next day does not find so much to undo before it can make its own advance. Thus the whole effect in melting the snow would be greater upon that hemisphere whose summer happens to be the more intense.

19. It would appear then that on Mars not only has the eccentricity no tendency to foster the retention of an extensive ice-cap about the pole of that hemisphere which has its summer solstice near perihelion, but that the permanent accumulation there is actually less than at the opposite pole.

20. Now suppose the total deposit of ice in winter to increase. Call

a, the southern cap at its maximum.

b, the same at its minimum.

a_1 and b_1 the respective maximum and minimum for the northern cap.

x the increased ratio of deposition, where $x > 1$: then

$a - b$ equals the amount of the southern cap melted during the summer.

$a_1 - b_1$ equals the same for the northern cap.

$xa - (a - b)$ will then represent the size of the southern cap at its new minimum, and

$\frac{xa - (a - b)}{b}$ or $\frac{(x - 1)\,a + b}{b}$ will be the ratio of the old minimum to the new. The ratio of the old maximun to the new is $\frac{xa}{a}$ or x

Now $\frac{(x - 1)\,a + b}{b} > x$, for if it were equal to it we should have

$(x - 1)\,a + b = bx;$

whence $(x - 1)\,a = (x - 1)\,b$ and since $a > b$ the first member would exceed the second.

Thus the minimum would increase at a faster rate than the maximum with increased deposit.

For the northern cap we have similarly

$$\frac{(x - 1)\,a_1 + b_1}{b_1}$$

The similarity of the expressions shows that the same result would hold here too.

But furthermore we have for the ratio of the maximum-minimum ratio of increase in the two caps respectively:

$$\frac{(x - 1)\,a + b}{b} \quad \text{to} \quad \frac{(x - 1)\,a_1 + b_1}{b_1}$$

The first member exceeds the second, for

$$\frac{(x - 1)\,a}{b} + 1 > \frac{(x - 1)\,a_1 + b_1}{b_1}$$

Since

$$\frac{a}{b} > \frac{a_1}{b_1}$$

So that the minimum increases relatively to the maximum faster in the southern hemisphere than in the northern one. And as this relative increase never changes sign, as the precipitation increases a time must come when the southern minimum will actually exceed the northern one in size and do so more and more, indefinitely.

Whence we find ourselves facing the interesting conclusion that with precipitation increased equally over the whole planet the size of the perpetual ice-cap at the southern pole would finally surpass that about the northern one. Whereas, then, with moderate precipitation the hemisphere with the extremes of summer and winter climate would have the less perpetual ice of the two; with more precipitation the result would be reversed.

21. On the earth this greater precipitation is made possible by the greater amount of water on the surface. Thus a glacial period might be produced with us under the very same conditions which would bar it on Mars. It would come about in consequence of the eccentricity of the orbit, but not chiefly because of that eccentricity. Rather, we may say, because of the amount of moisture capable of being manufactured. For were the moisture to fall below a definite amount, not only would no glacial period result no matter what the eccentricity, but actually a sort of anti-glacial epoch would be brought about by that very same cause.

Croll distinctly emphasizes the fact that it is the indirect not the direct effect of the eccentricity that causes a glacial period. This indirect effect he follows through increased precipitation to change of the winds and lastly to change of oceanic currents. What the present study of the problem appears to point out is that increased precipitation alone, from any cause whatever, is competent to the task.

22. Here, then, we have a remarkable reversal in arctic conditions from glacial to something not unakin to its opposite, due directly, not to change in eccentricity, though it presupposes eccentricity in the process, but to a greater or less abundance of water. And water plays a part in the performance of this act in each of its three forms—as gas, as liquid and as solid. As a gas, the lesser amount of it—for I believe it to be less in amount on Mars than with us, though relatively to the other two states of the substance greater—acts to keep the day-sky clear, the night-sky cloudy, and thus to foster the summer melting which results in a diminution of permanent ice. As a liquid, in which state it is certainly much scarcer

than with us, its relative absence causes a dearth of deposition which is the most important factor in establishing the conditions we have seen to exist. Lastly as a solid, the comparative lack of permanent ice-fields tends to keep the climate in a relatively genial condition and thus to allow the other two forms the greater play. Though the last seems but a passive partner, an acquiescer more than active accomplice, its *rôle* is not the least vital of the three. There is no doubt that the climate of our own arctic and antarctic regions is boreal to an extent far surpassing what mere absence of sun could cause. It is the storage of ice, the actual cold locked up in that substance in those polar prisons that is the true climatic controller of the extreme north and the extreme south.

23. From the mode of melting of the Martian polar caps, it is clear that we could have predicted a general dearth of bodies of water upon the planet from that evidence alone. We ought to have seen that so much was unmistakably written in the record open to our inspection. But other evidence presented itself first. So that we were already in possession of decisive testimony before the polar phenomena got a hearing.

Already we had come to the conclusion that what were formerly thought to be oceans, the-blue green markings, were not in reality seas, but vast tracts of field or forest. Many things testified to this; but not to weaken the argument by multiplying the proofs, it may suffice to say that permanent dark lines traverse them, and coincidently traverse the idea that they can be seas. At the same time they change color with the season, as vegetation would do. As autumn advances they fade from green to gold, and with the spring grow green again. Our own forests could look no other viewed across the millions of miles of separating space.

Change implies air, and vegetal change water to boot. Thus there is some water on Mars, though there is not much.

24. After the phenomena of the maxima and minima of the caps, the next peculiarity connected with them is the eccentring of the southern one. And this distinction is the more significant from its not being shared by the northern. The northern cap sits squarely upon its pole. The southern, on the other hand, is markedly eccentric to the axis of rotation. Its centre lies some seven degrees from the geographical pole over toward a point in about longitude 54°. Since then the two do not agree to differ, but are each idiosyncratic, it is clear that the cause cannot be one common to

both, but must consist in some peculiarity of the southern cap. Furthermore it must be some very general condition, for the eccentring is not confined to any one era or stage in the existence of the cap. It is observable from the time the cap is at its widest to the supreme moment of its decay. Nor does it shift its place to any extent throughout the shrinking, till the cap's size becomes so small that a trifling preponderance here or there in longevity unduly expresses itself in longitude. Such constancy of position shows that the whole accumulation is eccentrically placed, and not simply that some part is so locally conditioned as to outlast its fellows.

25. To account for the phenomenon, analogy tempts us to jump to the conclusion that elevation is responsible for the survivorship. And so it has been thought to be by many who have philosophized on the subject. For this would be the fact on earth, and the same we are, therefore, prone to impute to Mars. But consideration shows that such cannot be the case.

Cold increases with ascent above sea-level because the enveloping blanket of air or rather of water vapor thins out as we rise. On the earth in latitude 45° an elevation of a couple of miles is usually enough to bring one into the region of perpetual snow. But on Mars this would not be the case. On Mars the cold could not increase thus with the speed it does on earth. It is possible to affirm this without any regard to the actual amount of atmosphere upon that planet. For it is a simple matter of physics with which we have to do.

26. The mere mass of a planet decides the distribution of its atmospheric envelope. It does this irrespective of what the amount of that envelope may be. No matter how dense or how rare the air be at the planet's surface, the air diminishes upward by a law which depends directly and primarily upon the planet's mass. This law is found as follows:

Since the density of the air varies primarily as the pressure put upon it, we have at the point, if D denotes the density, p the pressure and g the force of gravity

$$\frac{dp}{dx} = \frac{c\,dD}{dx} = -ap = agD$$

whence

$$\frac{dD}{D} = agdx$$

The minus sign denotes that x diminishes as D increases. If we assume $a = 1$ we have

$$\frac{dD}{D} = -gdx$$

whence

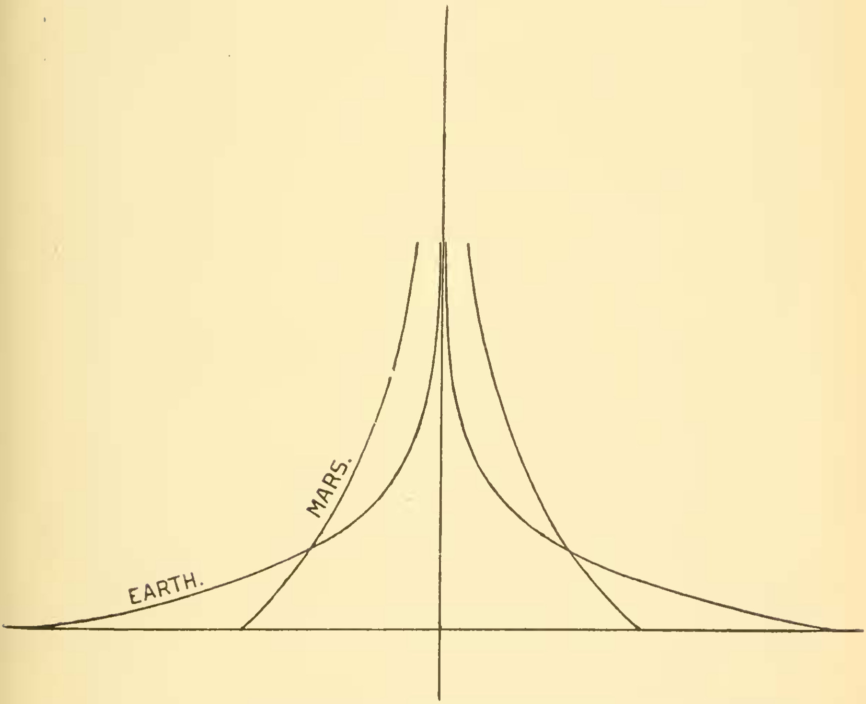
$$\int \frac{dD}{D} = \log D = -gx$$

or

$$D = e^{-gx}$$

For another planet we have in the same way

$$D = e^{-gx}$$



Curves showing variation in density of atmospheres on the Earth and on Mars.

Thus the height necessary to bring about the same relative amount of density upon two planets varies inversely as their respective surface gravity.

(I do not here consider temperature, which, according to some researches of my friend, Prof. Story, may possibly set superior limits to all planatory atmospheres.)

27. In consequence of this to compass a result for which a moderate ascent would suffice on earth, an immoderate one must be made on Mars. For gravity there being but 2⁄3 our own, nearly three times the rise is necessary. A Mt. Everest would stand for an Etna and something no less than eight miles high for a Mt. St. Elias. If such peaks existed, they could not fail of detection. Nevertheless none have been made out, nor are there any certain signs of even much lesser elevations. What have been most supposed to suggest them—the projections which, illuminated by slant lightning across the sunset or sunrise edge of the disk, stand out as bright points upon the terminator—do not tally with the look of hills, but are best explained by cloud. For they change in aspect only as clouds could contrive to do. Nor are other indications of possible mountains more expressive. Indeed, from every point of view Mars presents itself to us as futilely flat.

28. Dispensing, then, with earthly analogies we must look to Mars itself for explanation. Surveying the surface with this intent we presently note one trait which marks off the southern from the northern hemisphere—the relative absence in the latter of blue-green areas. It is, indeed, not a little odd how devoid the one-half of its globe is of what the other makes so fair a showing. The great mass of dark markings are to be found on that part of the planet which lies between the equator and the south pole.

29. Pursuing the subject, we find further that the blue-green regions are widest, reaching both farther down and higher up, between longitudes 300° and 90°. Here these regions stretch away to or fade into the arctic circle. Now it is in the centre of these longitudes, half way, roughly, across the breadth of the blue-green, that is found the centre of the southern snow-cap. Bowed toward this region, it evidently acknowledges some compelling potency there. And the continuance of the obeisance from the cap's beginning to its end points to a cause itself continuous.

30. The blue-green areas are, without doubt (see 23), vast vegetation bottoms. Though the dip is unquestionably but slight, it suffices to drain into them sub-ærially or surface-wise such moisture as may be present in the neighborhood. Whence their clothing of grass or forest or what does for these in Martian flora, their

like-tinted summer habiliment of green. Bottom-lands, not elevations then, are the cause of the snow's survival.

We are next concerned, therefore, with the way in which they may bring such result about. Just as it is not height but depth that determines the deposition, so it does this in quite unlike a manner. For by its indirect effects, more than by its direct efficiency, does it prove potent. Moisture in the air, it is true, flows into these lower levels because they are such, being hollows in the atmospheric ocean-bed. And they are such for water vapor over and above what they are for air, inasmuch as water vapor, though the lighter gas, is found most copious near the surface, thinning out more rapidly than the rest of the air upward. Depression is not so slight a factor as we proved elevation to be, because of this greater thinning out of moisture upward. But, even so, difference of level does directly but a part of the business. Indirectly depressions do something more: they start vegetation. Vegetation itself then takes a hand in the matter. Due to the humidity originally, once on the ground it reinforces the latter's action. For as a part of its life economy the plant is busied in pumping up water from the earth for the sake of the substances held there in solution which it absorbs, and setting the residue free allows it to evaporate away. Thus the moisture attracted to the spot is returned to the air about it, to be again deposited on provocation.

The deposit would not probably take the shape it does on earth. So thin, undoubtedly, is the air upon the surface of Mars that a precipitation in the form of rain or snow would seem not so likely a method of deposit as that other form dependent on contact which we know as dew or hoar-frost. In which case the deposit would occur nearer the place of generation, since it would offer less chance to be wafted to the winds. Being in a valley, the wind would get less sweep, and plant growth would still more hinder and hamper its course; and, secondly, what moisture was caught up and snatched away would be unlikely to be precipitated elsewhere. It would eventually return, to begin its plant work once more. Somewhere not far to the northward, then, of the general reservoirs of humidity, the great blue-green regions, we should expect to find the greatest accumulation of hoar-frost. This is precisely where we observe the centre of the snow-cap.

31. That the little midsummer remnant of the south polar cap lies at some distance from the pole, proves its survival due not to

the fortune of its position, but to its own self-preserving thickness. Of the northern snows, on the other hand, what is left over from year to year owes its conservation solely to latitude. Thus the survival of the little snow that is left at the southern pole, instead of proving the potency of the eccentricity, actually accentuates its impotence. Were it not for the presence of the lowlands with the increased moisture they gather and bequeath, there would be no eternal snow around the southern pole at all.

32. Thus this second characteristic of the polar patches, the centring of the one, the eccentring of the other, corroborates and enforces the testimony borne by the maxima and minima. For it shows that the minima are in truth more accentuated than they appear to be. The little minimum at the south pole would vanish entirely every year, instead of sporadically, were it not for local causes.

33. Our survey of the Martian polar caps, then, leads us to some curious conclusions. It starts with apparent contradiction of Croll's theory, to end in final confirmation of it. It comes to curse and stays to bless. But it does more. It shows that eccentricity of orbit by itself not only causes no universal glaciation, but actually produces on occasion the opposite result in more than offsetting by summer proximity what winter distance brings about. Eccentricity needs water and a great store of it as handmaid before its glacial work can be accomplished. Could our earth but get rid of its oceans, we, too, might have temperate regions stretching to the poles.

Stated Meeting, December 7, 1900.

Vice-President Wistar in the Chair.

Present, 13 members.

A communication was made by R. W. Shufeldt, M.D., "On the Osteology of the Striges."

The following annual reports were read:

The Treasurer.

The Curators.

The Publication Committee.